Robust Design of a Catalytic Converter with Material and Manufacturing Variations

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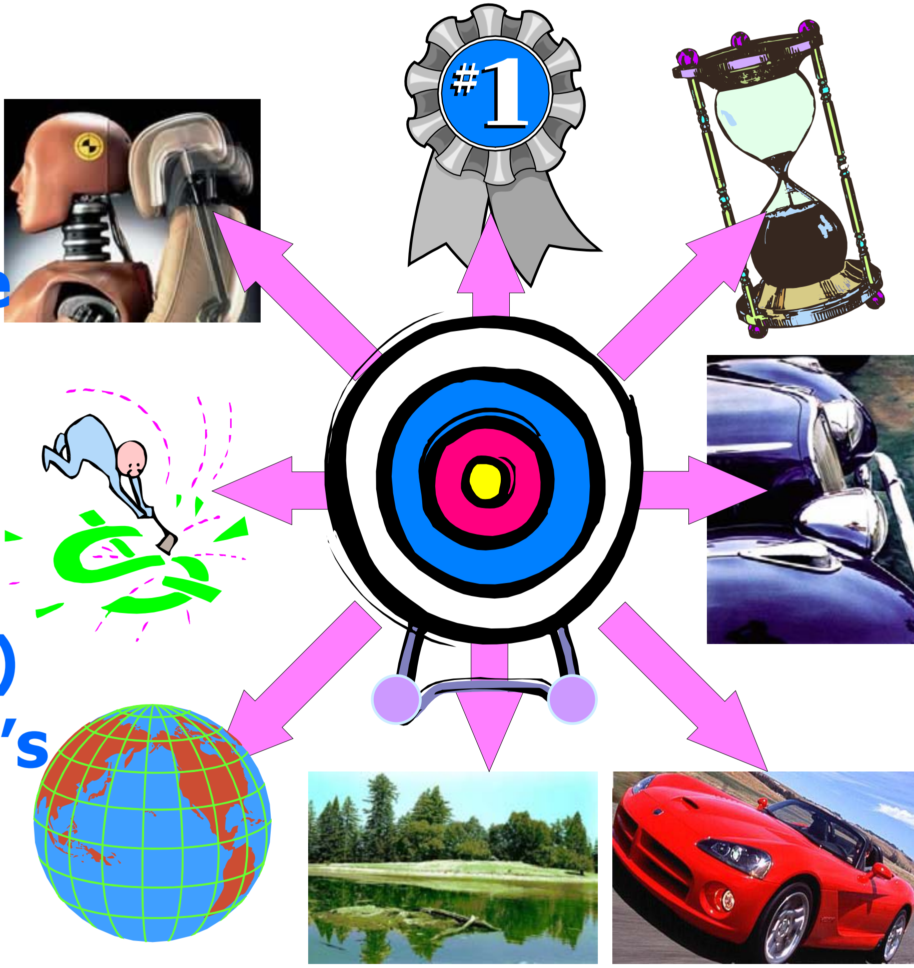
Contradicting Design Requirements

- **Cost**
- **Performance & safety**
- **Quality**
- **Time to market & short life cycle**
- **Environmental impacts**
- **Wow Aesthetics (creating waves of lust for the product, I got to have it …)**
- **Major Changes in Industry's Business Model**



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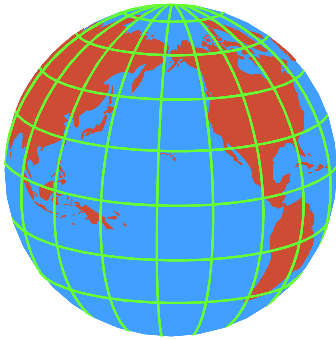
Changes in Automotive Industry's Business Model



- Cycle development time from concept to production is being compressed significantly
  - 1992: 60 months
  - 1996: 48 months
  - 2000: 18 months
- Vehicle designs are tailored to focused markets
- Vehicles are being manufactured more on a global scale
- Vehicles designed increasingly through multiple engineering sites around the world
- Need for enabling companies throughout the supply chain and extended enterprise to share information through a web-centric visualization approach

Improved Quality reduced Total Cost

Cost of Defect or Failure

- Lost Customers
- Liability
- Recalls
- Rework

Examples:

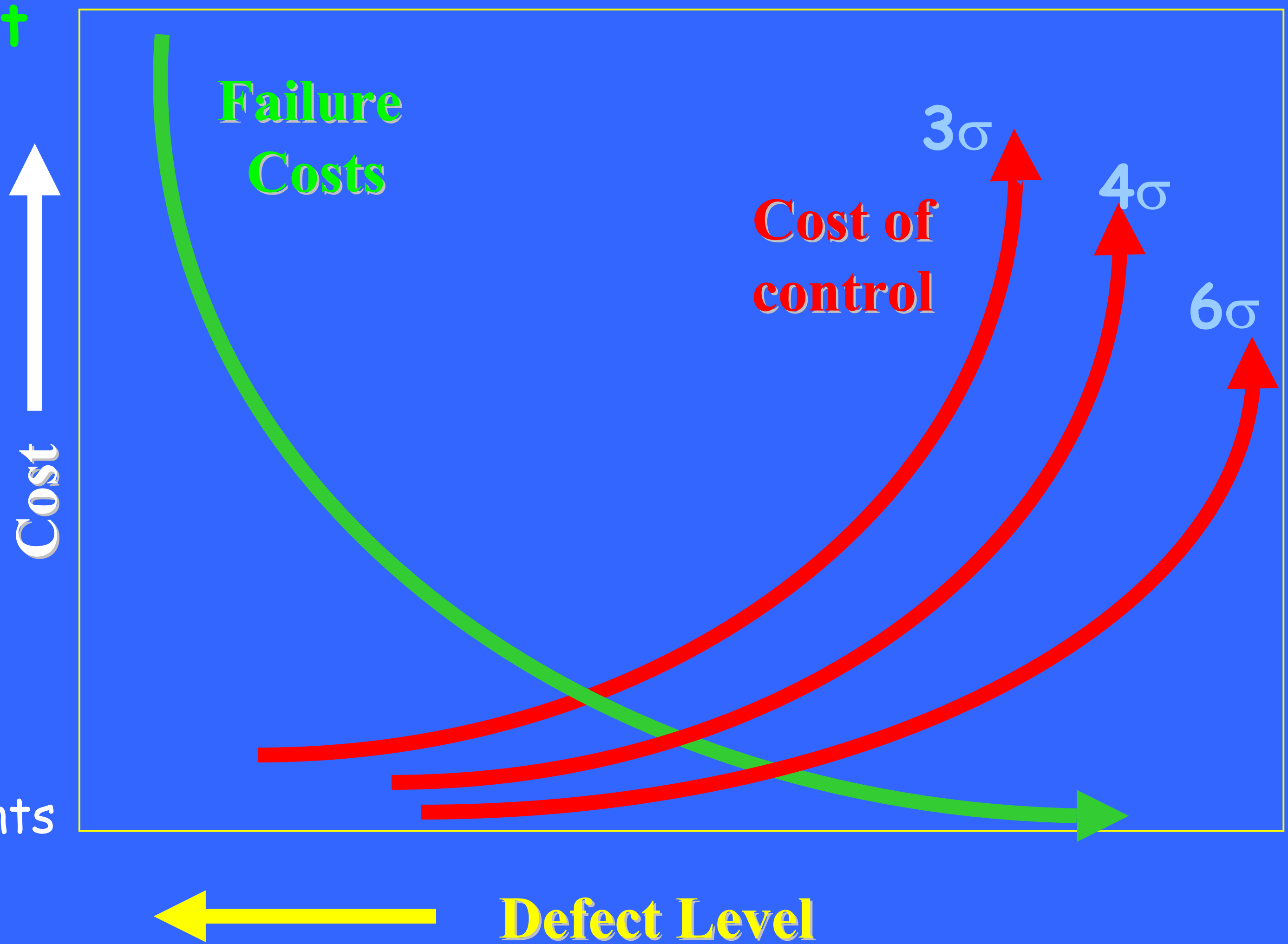
Titanic

Asbestos

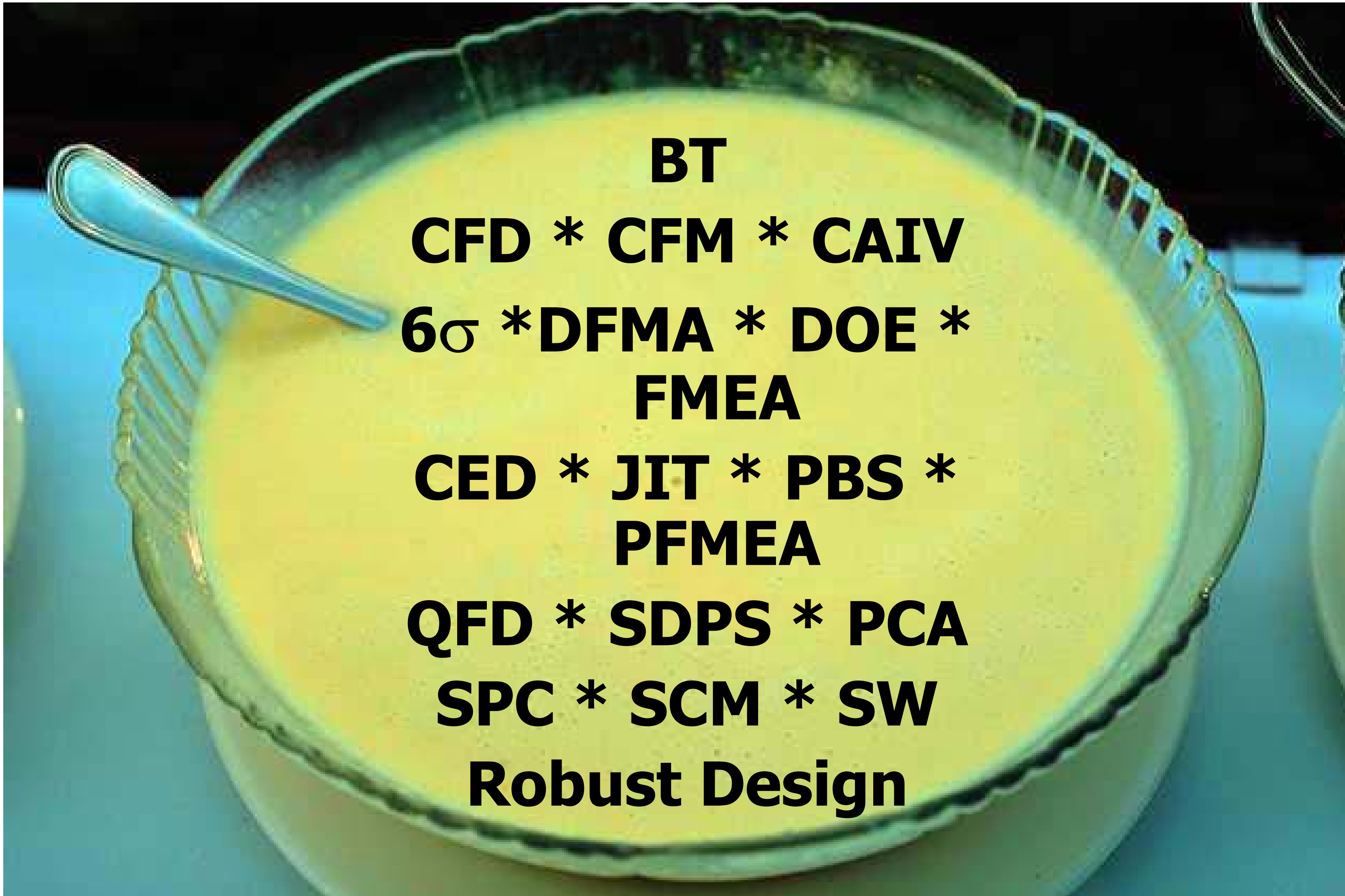
Breast Implants

Bhopal, India

…



Elements of Quality Process: The alphabet soup



Elements of Quality Management Process

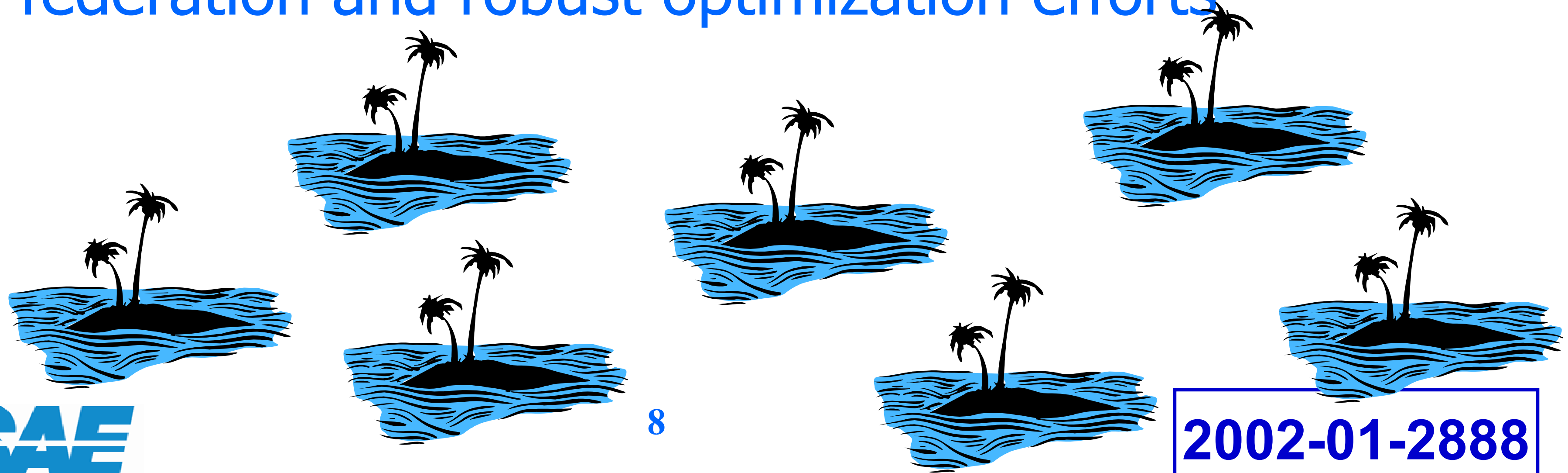
- Agile Improvement Process
- **Axiomatic Design**
- Benchmarking & Bench-trending
- Catch-ball
- Cellular Manufacturing
- Continuous Flow Development
- Continuous Flow Manufacturing
- Cycle Time Management
- Defect Reduction
- Design for Manufacturing and Assembly
- Design of Experiments
- Failure Modes effects Analysis
- Cause and Effect Diagrams
- Just In Time

- Performance Based Specifications
- Process Failure Mode Effects Analysis
- Quality Function Deployment
- Robust Design
- Self-Directed Work Teams
- Statistical Design Performance Simulation
- Process Capability Analysis
- Statistical Process Control
- Supply Chain Management
- Synchronous Workshops
- Theory of Constraints
- Thinking Process Reality Trees
- Total Productive Maintenance

Elements of Quality Management Process

Although all the elements of quality management process are closely connected they remain apart because they have been developed independently from each other

Integration of these tools is critical to the organization and necessary for successful federation and robust optimization efforts



Statistical Design Performance Simulation?

" You 've got to be passionate lunatics about the quality issue ..."

Jack Welch

"U.S. autos fight poor quality reputation ..."

Joe Miller / The Detroit News

" Product quality requires managerial, technological and statistical concepts throughout all the major functions of the organization ..."

Josheph M. Juran

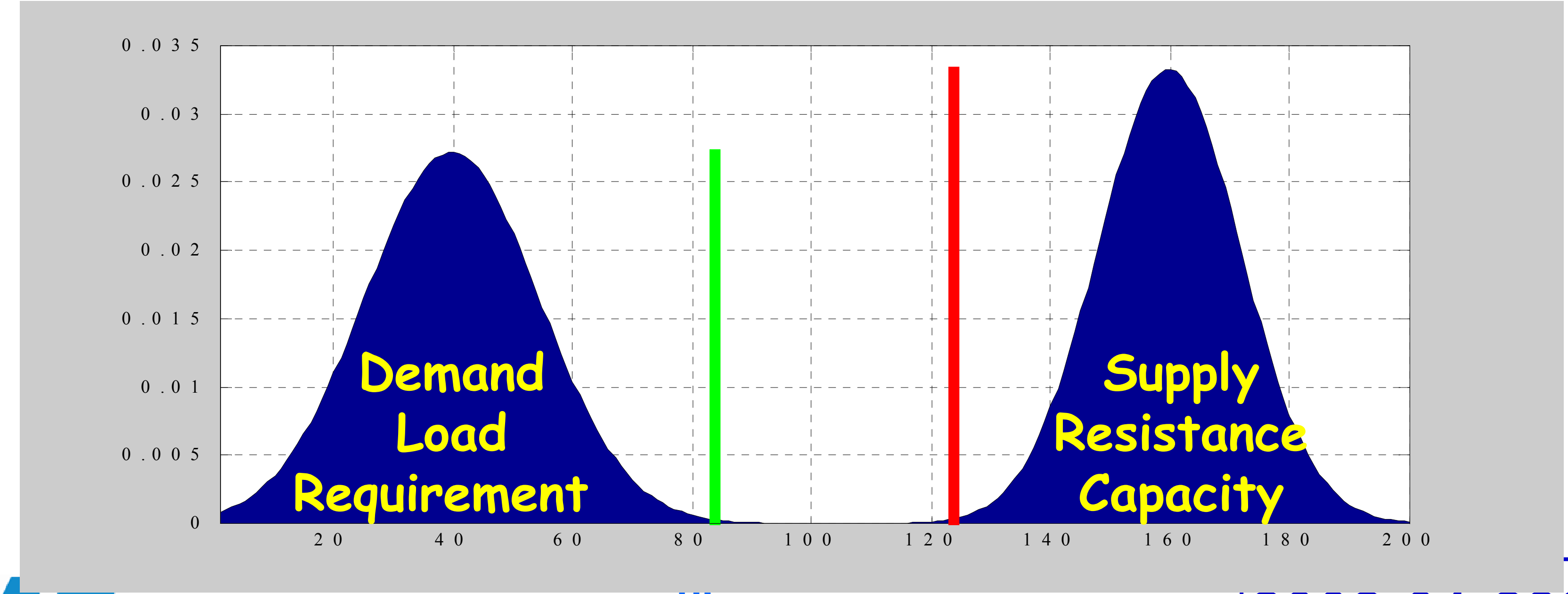
Variation (thickness, properties, surface finish, loads, etc.) is ... *THE ENEMY*

DOE, Six Sigma, Statistical FEA, Behavioral Modeling ... *THE DEFENCE*

Traditional Deterministic Approach

Accounts for uncertainties through the use of empirical Safety factors:

- Are derived based on past experience
- Do not guarantee safety or satisfactory performance
- Do not provide sufficient information to achieve optimal use of available resources



Quality - Robust Design

Definition of Robust Design:

Deliver customer expectations at profitable cost regardless of:

- customer usage
- variation in manufacturing
- variation in supplier
- variation in distribution, delivery & installation
- degradation over product life

Goals of Robust Design (shift and squeeze)

- Shift performance mean to the target value
- Reduce product's performance variability

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Tools for Robust Design

Design Of Experiments (DOE)

- Exploits nonlinearities and interactions between noise & control parameters to reduce product performance variability
- full factorial, fractional factorial, Monte-Carlo, LHC

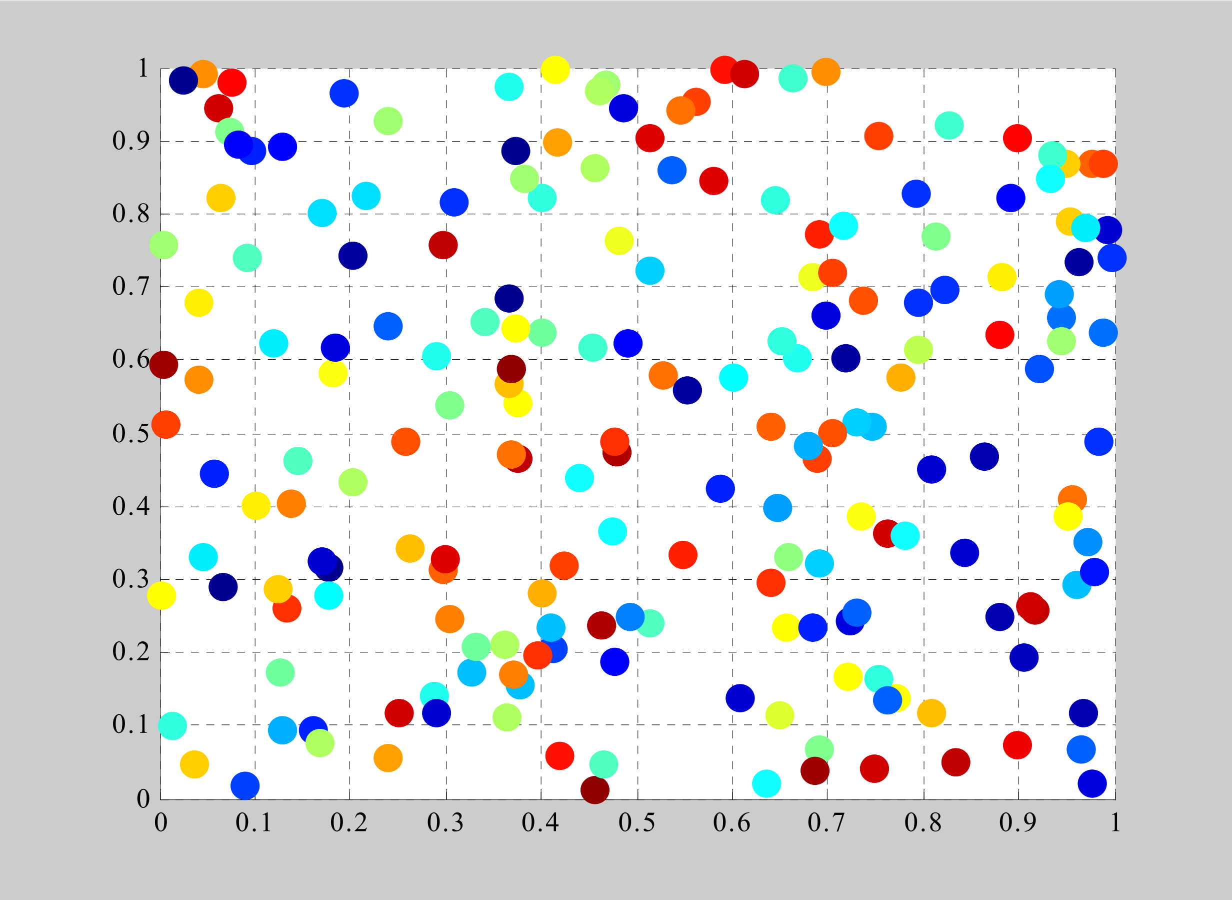
Response Surface Methods

- Central Composite Design
- Box-Behnken Design

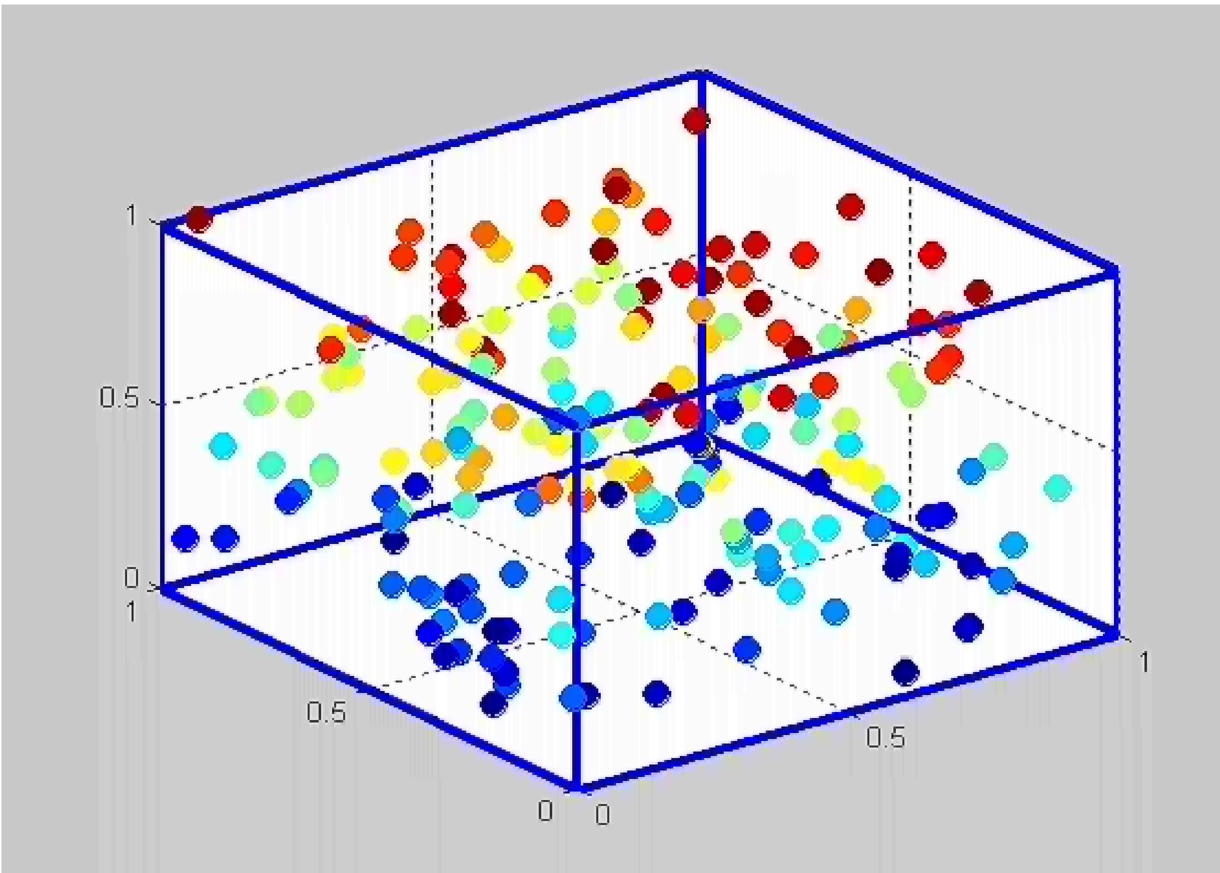
6-sigma design (Statistical Performance)

- Identifying & qualifying causes of variation
- Centering performance on specification target
- Achieving Six Sigma level robustness on the key product performance characteristics with respect to the quantified variation

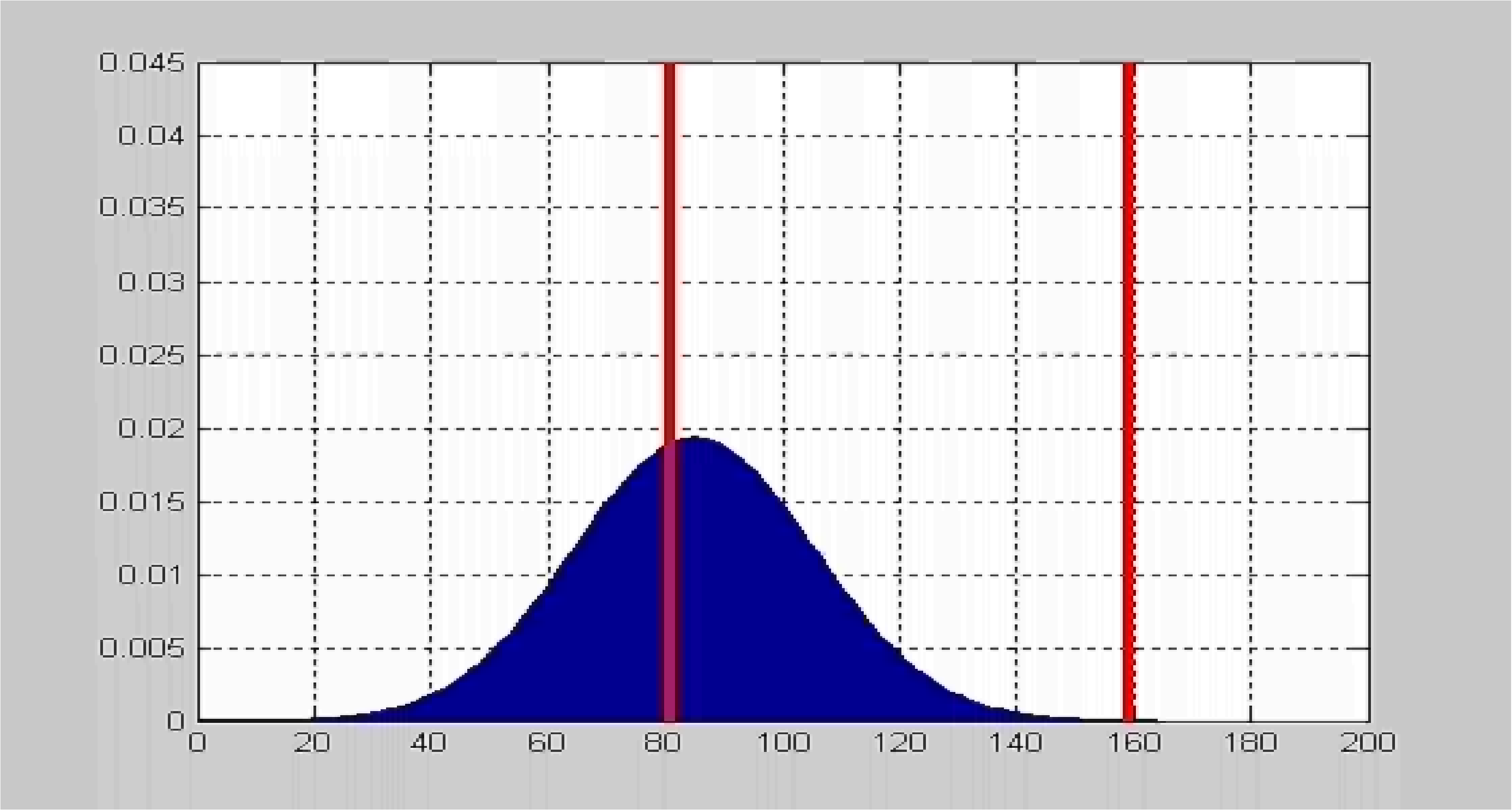
Design Space Exploration 2 Variables



Design Space Exploration 3 Variables



Statistical Performance: Shift and Squeeze



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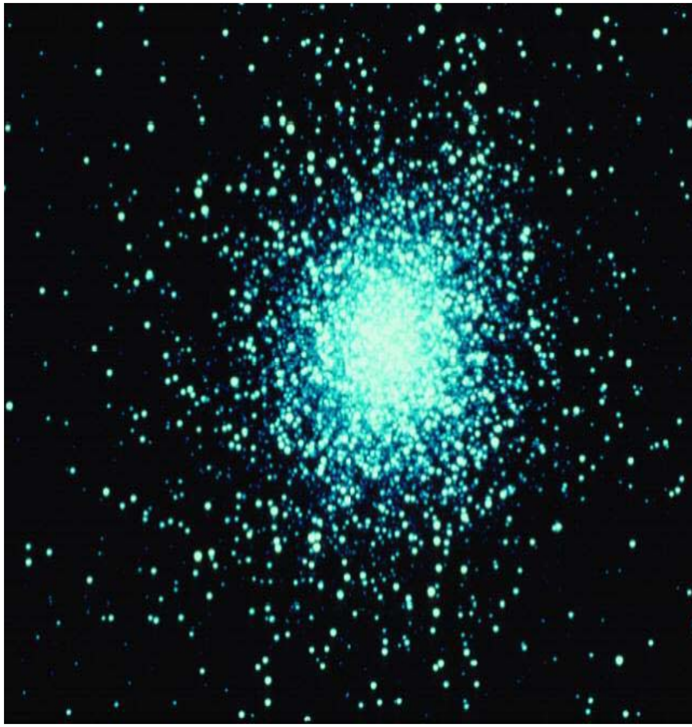
Identifying Noise & Control Parameters

Noise parameters:

Factors that are beyond the control of the designer

- material property variability
- manufacturing process limitations
- environment temperature & humidity
- component degradation with time
- ...

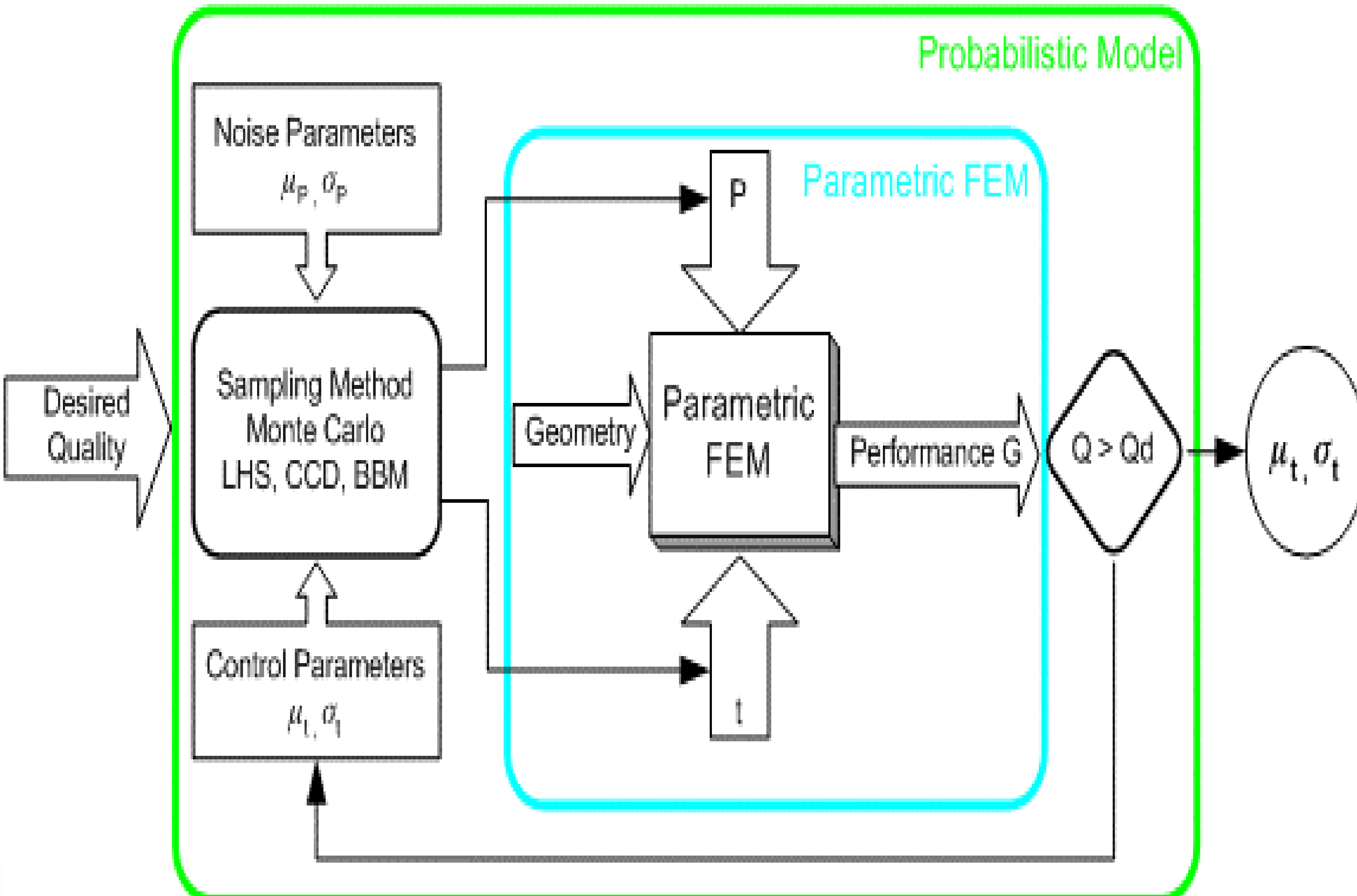


Control Parameters:

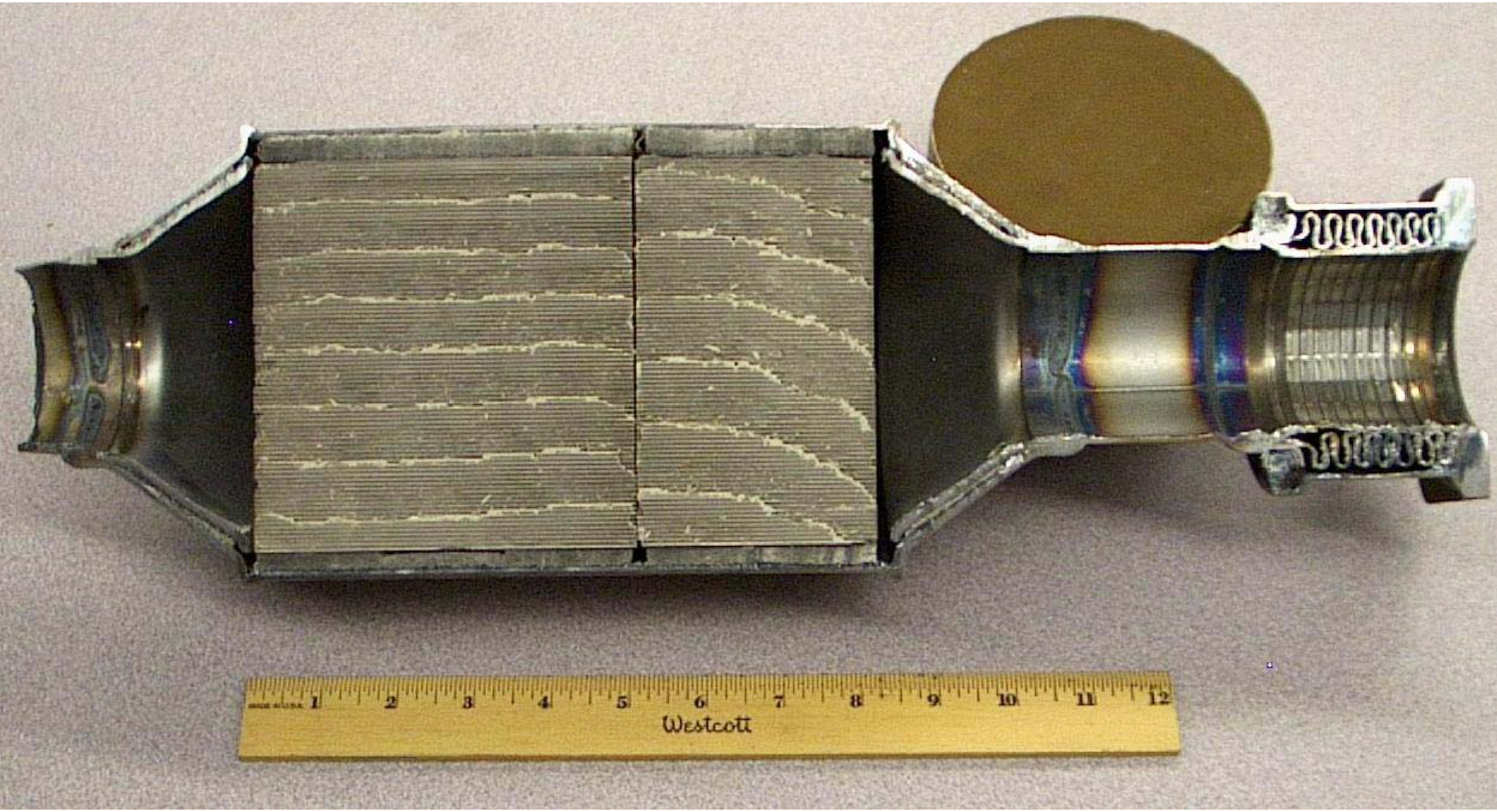
Factors that the designer can control

- geometric design variables
- material selections
- design configurations
- manufacturing process settings
- ...

Workflow for Probabilistic Design System



Catalytic Converter Section

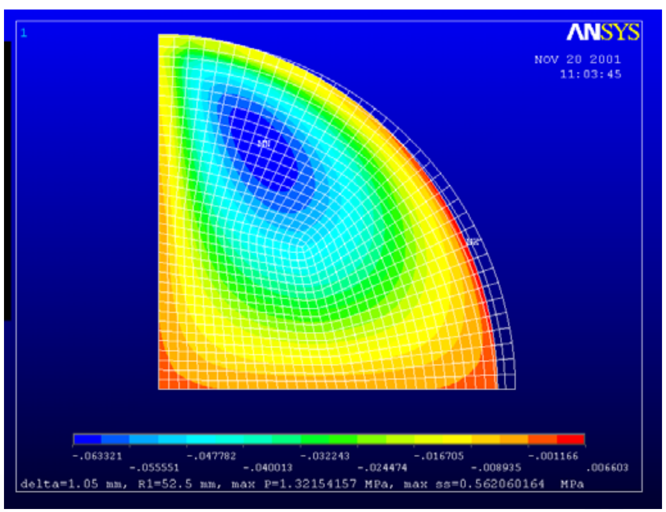


Catalytic Converter Section

Catalytic Converter Section

Catalytic Converter Failure Avoidance Study

If $\Delta = \Phi_{max} - \Phi_{min}$, $\tau_{allowable}$ exhibits a given variation and $G = \tau_{allowable} - \tau_{max}$, identify the **supplier specification** (maximum standard deviation of Δ) in order to achieve six-sigma quality (positive values of the performance function $G = \mu_G - 6^* \sigma_G > 0$



$\Phi_{max,min}$ = max and min diameters of a catalytic converter substrate

G = performance function

$\tau_{allowable}$ = allowable shear stress

τ_{max} = maximum shear stress

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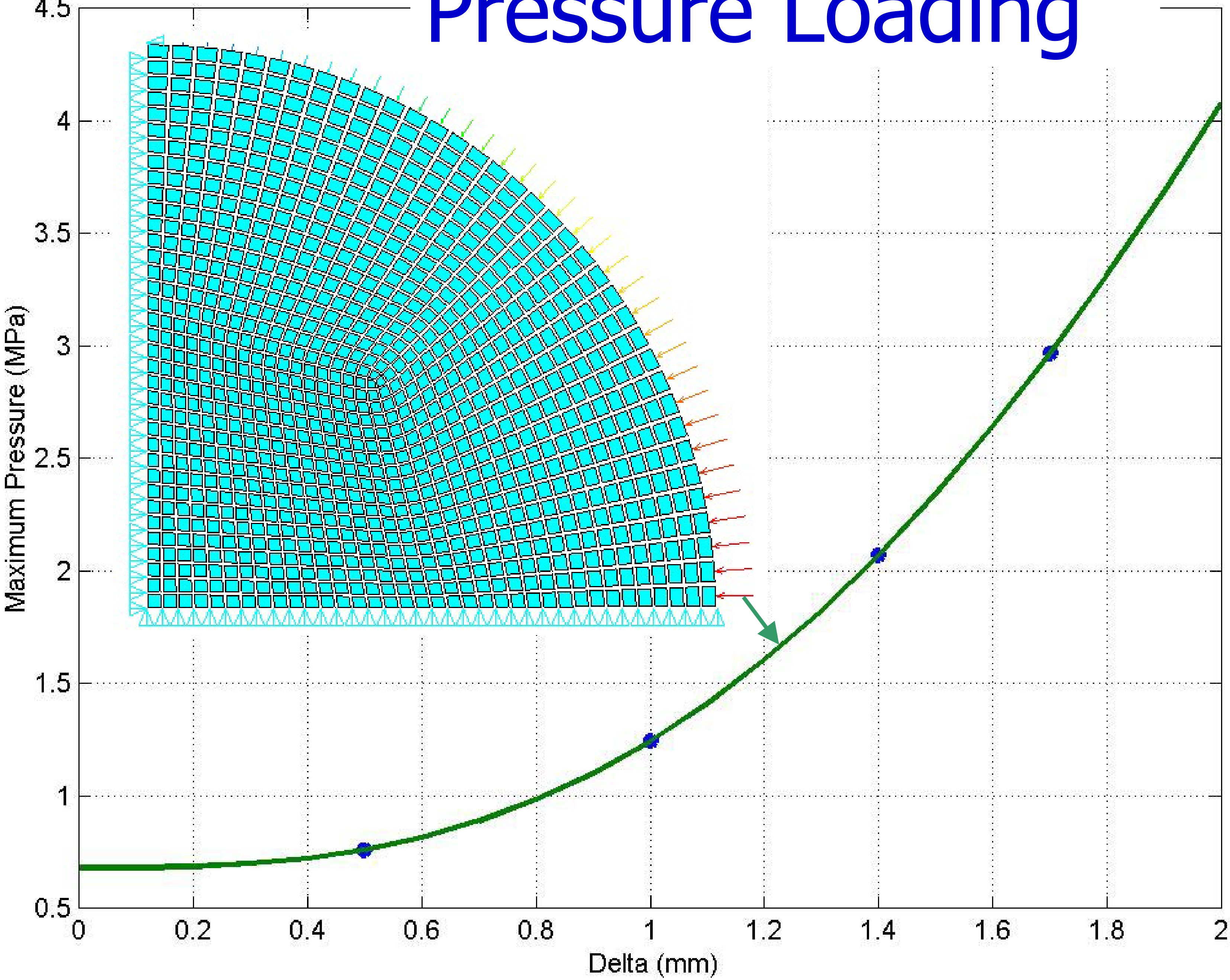
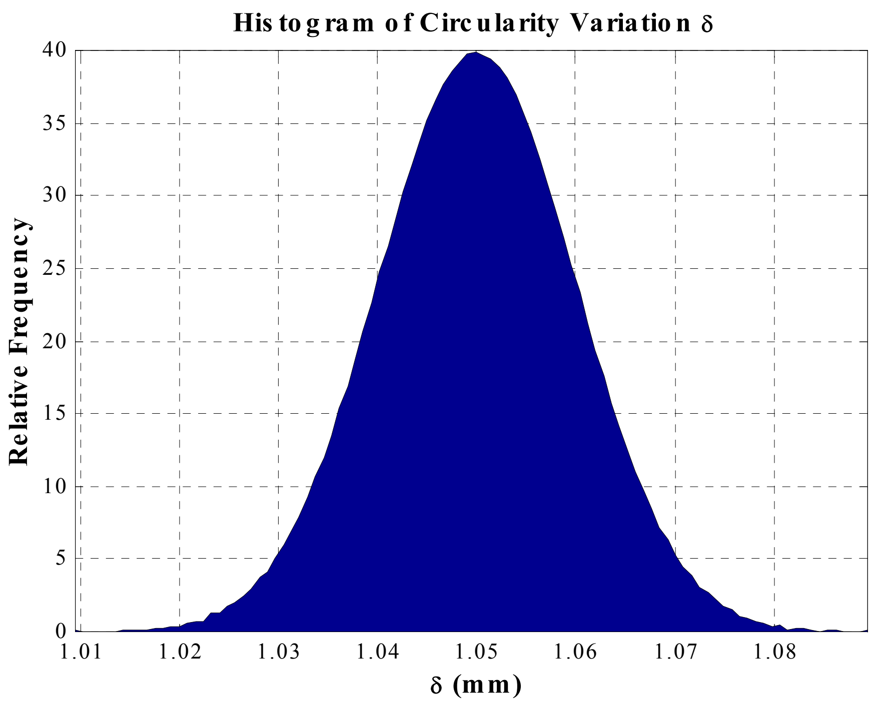
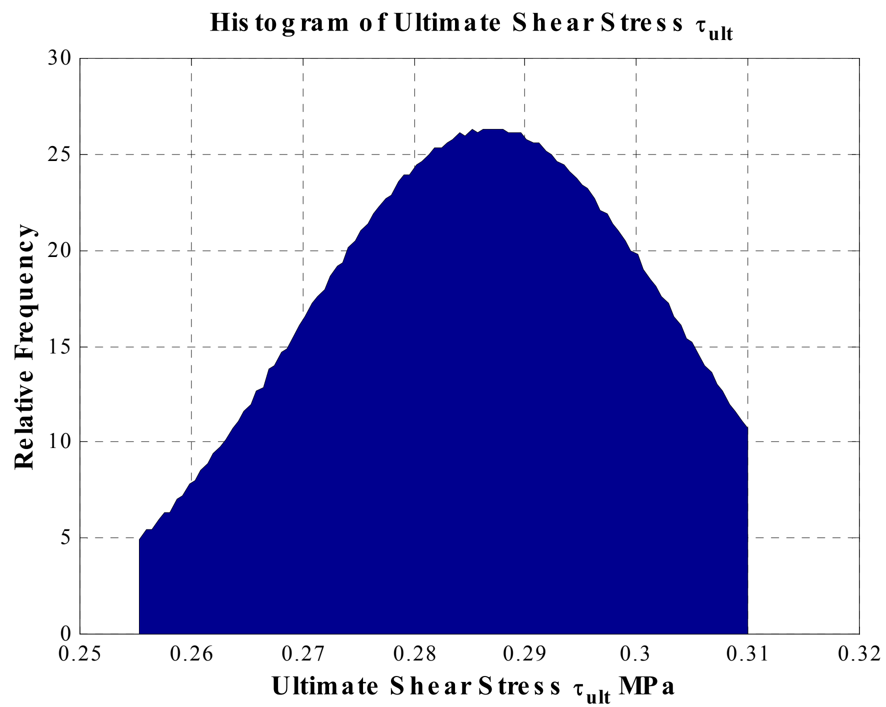
Pressure Loading



Circularity and Ultimate shear stress variation





Control Parameter

Noise Parameter

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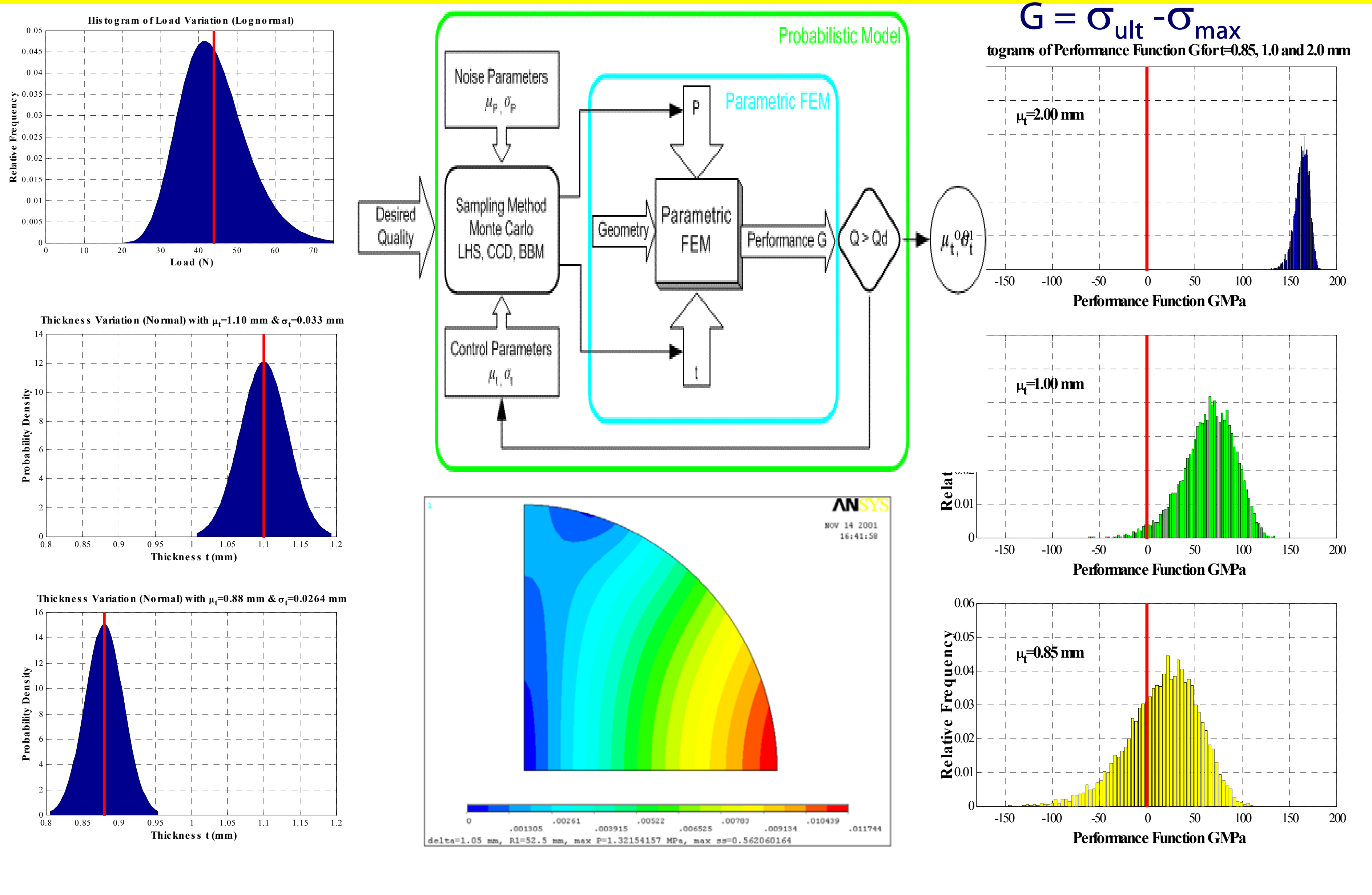
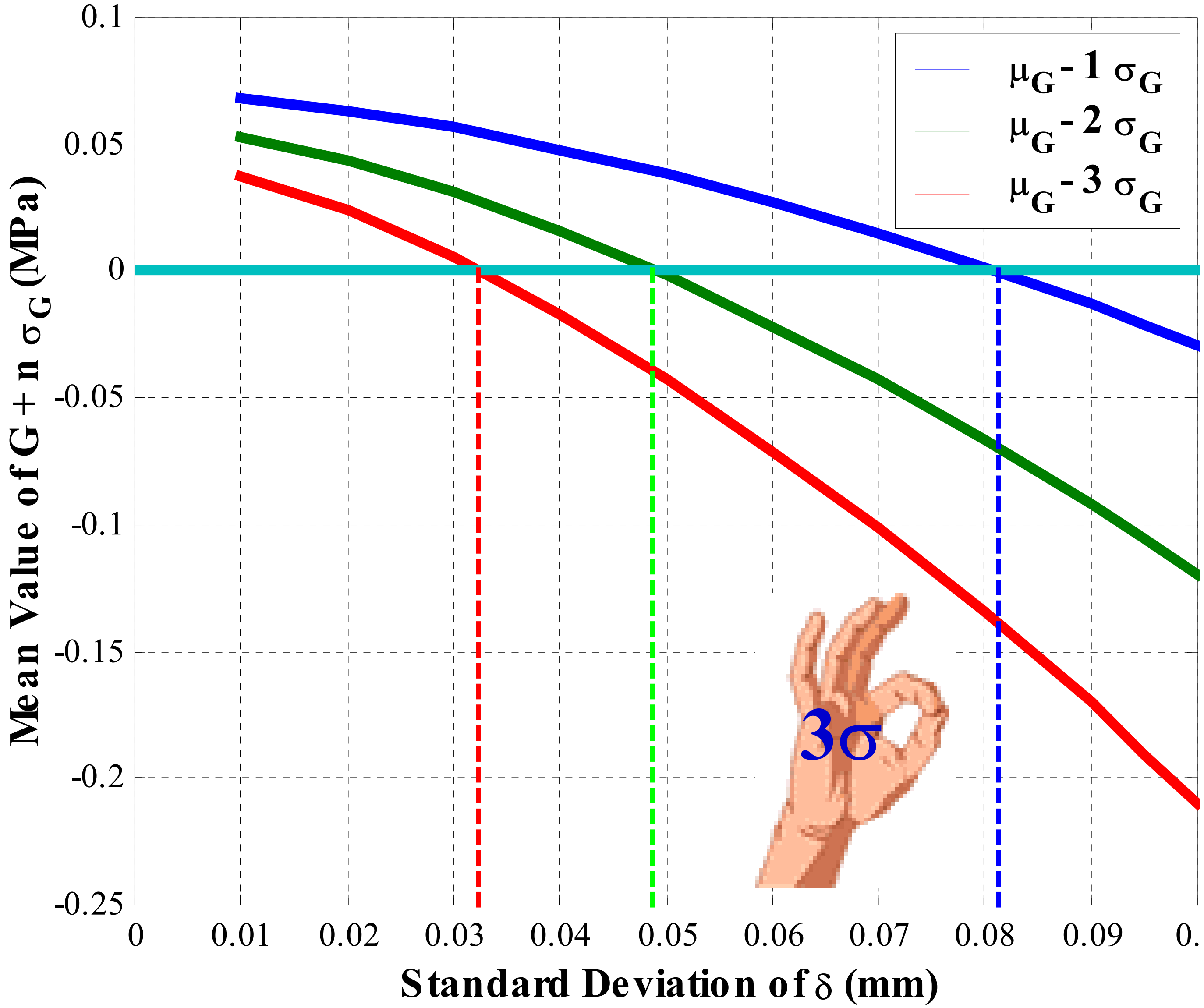
Workflow for Robust Design System

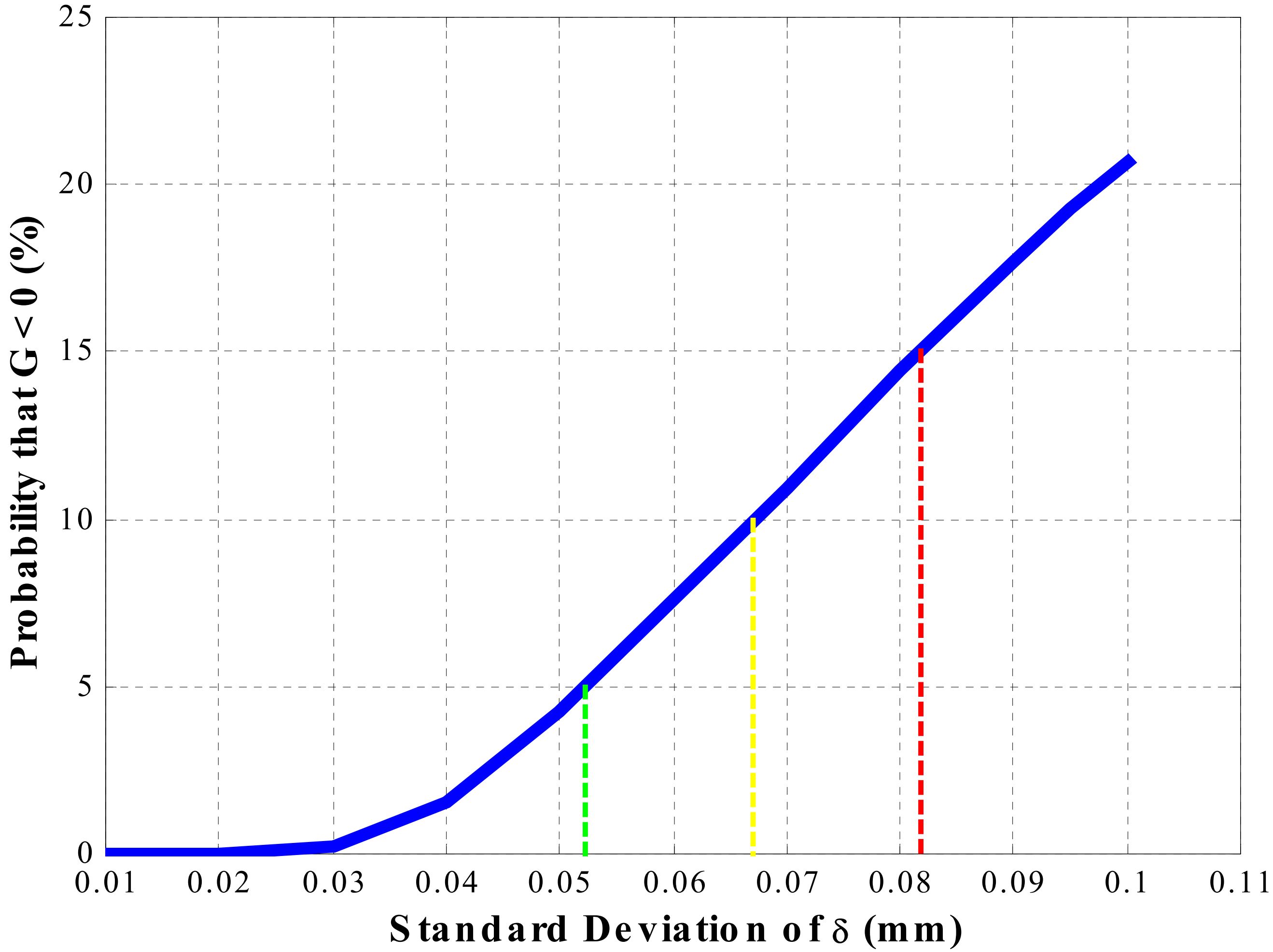


Design Variable selection that meets desired quality criteria

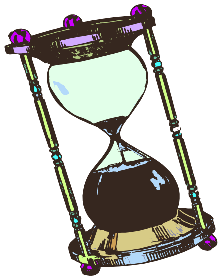
Performance Function $G = \sigma_{ult} - \sigma_{max}$



Probability that the Performance Function Is Less Than Zero Versus the σ_δ



Conclusions



- Automated probabilistic design process that enables engineers to identify better designs that meet the performance objectives and are less sensitive to manufacturing variations.
- For a given sigma quality level (i.e. six-sigma) or for a given reliability goal (i.e. 95%) the maximum standard deviation of the circularity variation can be determined using the design process described.
- A good correlation between these results and the verification tests was found.
- By incorporating the physical scatter into the model, the risk of failing legal or consumer tests can be minimized.